Calibration & Editing

George Moellenbrock

Ninth Synthesis Imaging Summer School
Socorro, June 15-22, 2004

Why Calibration and Editing?

• Synthesis radio telescopes, though well-designed, are not perfect (e.g., surface accuracy, receiver noise, polarization purity, stability, etc.)
• Need to accommodate engineering (e.g., frequency conversion, digital electronics, etc.)
• Hardware or control software occasionally fails or behaves unpredictably
• Scheduling/observation errors sometimes occur (e.g., wrong source positions)
• Atmospheric conditions not ideal (not limited to ‘bad’ weather)
• RFI

Determining instrumental properties (calibration) is as important as determining radio source properties

From Idealistic to Realistic

• Formally, we wish to obtain the visibility function, which we intend to invert to obtain an image of the sky:

\[ V(u, v) = \int \mathcal{F}(l, m) e^{-2\pi i (u l + v m)} dl \, dm \]

• In practice, we correlate (multiply & average) the electric field (voltage) samples, \( x_i \) and \( x_j \) received at pairs of telescopes \( (i, j) \):

\[ V_{ij} = \langle K_{ij} x_i(t) \cdot K_{ij}^* x_j^*(t) \rangle_{(t)} = V(u_i, v_j) \]

– \( K_i \) is geometric compensation (delays, fringe rotation) which sets the position on the sky of the phase center
– Averaging duration is set by the expected timescales for variation of the correlation result (typically 10s or less for the VLA)
• Single radio telescopes are devices for collecting the signal \( x(t) \) and providing it to the correlator.

What signal is really collected?

• The net signal delivered by antenna \( i, x_i(t) \), is a combination of the desired signal, \( s(t, l, m) \), corrupted by a factor \( J(t, l, m) \) and integrated over the sky, and noise, \( n(t) \):

\[ x_i(t) = \int J(t, l, m) s(t, l, m) \, dl \, dm + n_i(t) \]

\[ = \tilde{x}_i(t) + n_i(t) \]

• \( J(t, l, m) \) is the product of a host of effects which we must calibrate
• In some cases, effects implicit in the \( J(t, l, m) \) term corrupt the signal irreversibly and the resulting data must be edited
• \( J(t, l, m) \) is a complex number
• \( J(t, l, m) \) is antenna-based
• Usually, \( |n_i| \gg |s| \)

Correlation of realistic signals

• The correlation of two realistic signals from different antennas:

\[ \langle K_i x_i(t) \rangle_{(t)} = \langle K_i \rangle \langle x_i(t) \rangle_{(t)} + \langle [K_i x_i(t) n_t(t)] \rangle \]

\[ = \langle K_i x_i(t) \rangle_{(t)} + \langle [K_i x_i(t) n_t(t)] \rangle \]

• Noise doesn’t correlate—even if \( |n_i| \gg |s| \); the correlation process isolates desired signals:

\[ = \langle K_i x_i(t) \rangle_{(t)} \]

• In (integral), only \( x_i(t, l, m) \) from the same directions correlate (i.e., when \( l_i, l_j, m_i, m_j \) are in common), so order of integration and signal product can be reversed:

\[ = \int \mathcal{F}(l, m) e^{-2\pi i (u l + v m)} K_i x_i(t) x_j^*(t) \, dl \, dm \]

Why calibration and editing?

• Formalism: Visibility, signals, matrices
• Solving the Measurement Equation
• Practical Calibration Planning
• Spectral Line Example / Calibration Evaluation
• A Dictionary of Calibration Components
• Editing and RFI
• Summary
Correlation of realistic signals (cont)

- Using the geometry of the situation, we can recast $s_i$ and $s_j$ in terms of the single signal, $s$, which arrived at each of the telescopes from the distant sky:

\[
V_i = \left[ \begin{array}{c} J_i \sin \theta_i \cos \phi_i \\ J_i \sin \theta_i \sin \phi_i \\ J_i \cos \theta_i \end{array} \right] \text{slim}\]

- On the timescale of the averaging, the only meaningful average is of the squared signal itself (direction-dependent), which is just the image of the source:

\[
\frac{1}{\Delta \tau} \int J_i J^* \text{slim}\]

- If all $J_i$ are zero, we of course recover the Fourier transform expression:

\[
\hat{V}(\bar{t}) = \frac{1}{\Delta \tau} \int J_i J^* \text{slim}\]

Full-Polarization Formalism (matrices)

- Need dual-polarization basis ($p,q$) to fully sample the incoming EM wave front, where $p,q \in \{X,Y\}$ (circular basis) or $p,q \in \{I,Q\}$ (linear basis):

\[
\begin{array}{cccc}
I_{in} = & I_{in} & I_{in} & I_{in} \\
I_{in} & 1 & 0 & 1 \\
Q_{in} & 0 & 1 & 0 \\
L_{in} & 1 & 0 & 1 \\
\end{array}
\]

- Devices can be built to sample these basis states in the signal domain (Stokes Vector is defined in “power” domain)

- Some components of $J_i$ involve mixing of basis states, so dual-polarization matrix description desirable or even required for proper calibration

Correlation of realistic signals (cont)

- The auto-correlation of a signal from a single antenna:

\[
\langle s_i, s_j \rangle = \langle \bar{V}_i \bar{V}^*_j \rangle = \left( \begin{array}{c} 1 \end{array} \right)
\]

\[
= \left( \begin{array}{c} \bar{V}_i \bar{V}^*_j \end{array} \right) = \left( \begin{array}{c} 1 \end{array} \right)
\]

- This is an integrated power measurement plus noise
- Desired signal not isolated from noise
- Noise usually dominates
- Single dish radio astronomy calibration strategies dominated by switching schemes to isolate desired signal

Full-Polarization Formalism: Signal Domain

- Substitute:

\[
\tilde{J}_i \rightarrow \tilde{J}_i = \left( \begin{array}{c} s_i \\ \phi_i \end{array} \right), \quad J_i \rightarrow \tilde{J}_i = \left( \begin{array}{c} J_{i+} \\ J_{i-} \\ J_{i0} \\ J_{i90} \end{array} \right)
\]

- The Jones matrix thus corrupts a signal as follows:

\[
\tilde{J}_i = \tilde{J}_i \tilde{J}_i^* = \left( \begin{array}{c} J_{i+} J_{i+}^* \\ J_{i-} J_{i-}^* \\ J_{i0} J_{i0}^* \\ J_{i90} J_{i90}^* \end{array} \right)
\]

- Omitting integral term

Full-Polarization Formalism: Correlation

- Four correlations are possible from two polarizations. The outer product (a "bookkeeping" product) represents correlation in the matrix formalism:

\[
\langle \bar{J}_i \otimes \bar{J}_j \rangle = \left( \begin{array}{c} J_{i+} J_{i+}^* \\ J_{i-} J_{i-}^* \\ J_{i0} J_{i0}^* \\ J_{i90} J_{i90}^* \end{array} \right) = \left( \begin{array}{c} 1 \end{array} \right)
\]

- A very useful property of outer products:

\[
\langle \bar{J}_i \otimes \bar{J}_j \rangle = \langle \bar{J}_i \otimes \bar{J}_j \rangle = \langle \bar{J}_i \otimes \bar{J}_j \rangle = \langle \bar{J}_i \otimes \bar{J}_j \rangle
\]

Full-Polarization Formalism: Correlation (cont)

- The outer product for the Jones matrix:

\[
\tilde{J}_j \otimes \tilde{J}_j^* = \left( \begin{array}{c} J_{i+} J_{i+}^* \\ J_{i-} J_{i-}^* \\ J_{i0} J_{i0}^* \\ J_{i90} J_{i90}^* \end{array} \right) = \left( \begin{array}{c} 1 \end{array} \right)
\]

- $J_i$ is a 4x4 Mueller matrix
- Antenna and array design driven by minimizing off-diagonal terms
Signal Correlation and Matrices (cont)

- And finally, for fun, the correlation of corrupted signals:
  \[
  \langle \tilde{J}_x \otimes \tilde{J}_y' \rangle = \langle \tilde{J}_x \otimes J_x' \rangle \langle \tilde{J}_y' \otimes \tilde{J}_y' \rangle \]

\[
\begin{bmatrix}
J_x'' & J_y'' & J_z'' & J_x'' & J_y'' & J_z'' & J_x'' & J_y'' & J_z'' \\
J_y'' & J_x'' & J_z'' & J_x'' & J_y'' & J_z'' & J_x'' & J_y'' & J_z'' \\
J_z'' & J_x'' & J_y'' & J_x'' & J_y'' & J_z'' & J_x'' & J_y'' & J_z'' \\
J_x'' & J_y'' & J_z'' & J_x'' & J_y'' & J_z'' & J_x'' & J_y'' & J_z'' \\
J_y'' & J_x'' & J_z'' & J_x'' & J_y'' & J_z'' & J_x'' & J_y'' & J_z'' \\
J_z'' & J_x'' & J_y'' & J_x'' & J_y'' & J_z'' & J_x'' & J_y'' & J_z'' \\
J_x'' & J_y'' & J_z'' & J_x'' & J_y'' & J_z'' & J_x'' & J_y'' & J_z'' \\
J_y'' & J_x'' & J_z'' & J_x'' & J_y'' & J_z'' & J_x'' & J_y'' & J_z'' \\
J_z'' & J_x'' & J_y'' & J_x'' & J_y'' & J_z'' & J_x'' & J_y'' & J_z''
\end{bmatrix}
\]

- UGLY, but we rarely need to worry about detail at this level—just let this occur “inside” the matrix formalism, and work with the notation.

The Measurement Equation

- We can now write down the calibration situation in a general way—the Measurement Equation:

\[
\tilde{V}^m_{ij} = \int \tilde{J}_i \otimes \tilde{J}_j' \sin \theta \langle \sin \theta \rangle d\theta d\phi d\chi
\]

- ...and consider how to solve it!

The Measurement Equation - Simplified

First, isolate non-direction-dependent effects, and factor them from the integral:

\[
\tilde{V}^m_{ij} = \int \tilde{J}_i \otimes \tilde{J}_j' \sin \theta \langle \sin \theta \rangle d\theta d\phi d\chi
\]

Next, we recognize that it is often possible to assume \( \tilde{J}_i \) = \( \tilde{J}_j' \) \( \sin \theta \langle \sin \theta \rangle \) and we have a relationship between ideal and observed Visibilities:

\[
\tilde{V}^i_{ij} = \int \tilde{J}_i \otimes \tilde{J}_j' \sin \theta \langle \sin \theta \rangle d\theta d\phi d\chi
\]

Solving the Measurement Equation

- The \( \tilde{J}_i \)'s terms can be factored into a series of components representing physical elements along the signal path:

\[
\tilde{V}^i_{ij} = \langle \tilde{J}_i \rangle \langle \tilde{J}_j' \rangle \sin \theta \langle \sin \theta \rangle d\theta d\phi d\chi
\]

- Depending upon availability of estimates for various \( \tilde{J}_i \)' terms, we can rearrange the equation and solve for any single term, if we know \( \tilde{V}^i_{ij} \):

\[
\tilde{V}^i_{ij} = \langle \tilde{J}_i \rangle \langle \tilde{J}_j' \rangle \sin \theta \langle \sin \theta \rangle d\theta d\phi d\chi
\]

- After obtaining estimates for all relevant \( \tilde{J}_i \) data can be corrected:

\[
\tilde{V}^c_{ij} = \langle \tilde{J}_i \rangle \langle \tilde{J}_j' \rangle \sin \theta \langle \sin \theta \rangle d\theta d\phi d\chi
\]

Antenna-based Calibration

- Success of synthesis telescopes relies on antenna-based calibration
  - \( \tilde{N} \) antenna-based factors, \( \tilde{N} \langle \tilde{N} \rangle \) visibility measurements
  - Fundamentally, only information that cannot be factored into antenna-based terms is believable as being of astronomical origin

- Closure: calibration-independent observables (diagonal components):
  - Closure phase (3 baselines):

\[
\begin{bmatrix}
\langle \tilde{J}_i \rangle \langle \tilde{J}_j' \rangle \sin \theta \langle \sin \theta \rangle d\theta d\phi d\chi
\end{bmatrix}
\]

- Closure amplitude (4 baselines):

\[
\begin{bmatrix}
\langle \tilde{J}_i \rangle \langle \tilde{J}_j' \rangle \sin \theta \langle \sin \theta \rangle d\theta d\phi d\chi
\end{bmatrix}
\]

- Tim Cornwell’s lecture “Self-calibration” (Wednesday)

- Beware of non-closing errors!
Planning for Good Calibration

- A priori calibrations (provided by the observatory)
  - Antenna positions, earth orientation and rate
  - Clocks
  - Antenna pointing, gain, voltage-pattern
  - Calibrator coordinates, flux densities, polarization properties
- Absolute calibration?
  - Very difficult, requires heroic efforts by visiting observers and observatory scientific and engineering staff
- Cross-calibration a better choice
  - Observe nearby point sources against which calibration components can be solved, and transfer solutions to target observations
  - Choose appropriate calibrators for different components; usually strong point sources because we can predict their visibilities
  - Choose appropriate timescales for each component

Simple (common) example, Gain and Bandpass:

\[
\begin{align*}
V_{\nu}^{\text{obs}} &= \left[B \odot B' \odot G \odot G'\right] V_{\nu}^{\text{ab恍}} \\
&= B \odot G \odot V_{\nu}^{\text{ab恍}}
\end{align*}
\]

“Electronic” Gain, \( G \)

- Catch-all for most amplitude and phase effects introduced by antenna electronics (amplifiers, mixers, quantizers, digitizers)
  - Most commonly treated calibration component
  - Dominates other effects for standard VLA observations
  - Includes scaling from engineering (correlation coefficient) to radio astronomy units (Jy), by scaling solution amplitudes according to observations of a flux density calibrator
  - Often also includes ionospheric and tropospheric effects which are typically difficult to separate onto themselves
  - Excludes frequency dependent effects (see \( B \))

\[
G^{\nu} = \begin{bmatrix} R^{\nu} & 0 \\ 0 & R^{\nu} \end{bmatrix}
\]

Bandpass Response, \( B \)

- G-like component describing frequency-dependence of antenna electronics, etc.
  - Filters used to select frequency passband not square
  - Optical and electronic reflections introduce ripples across band
  - Often assumed time-independent, but not necessarily so
  - Typically (but not necessarily) normalized

\[
B^{\nu} = \begin{bmatrix} b^{\nu}(\nu) & 0 \\ 0 & b^{\nu}(\nu) \end{bmatrix}
\]

Spectral-Line Calibration Example

- Observation: total intensity spectral line imaging of weak target
  - A weak target source (2)
  - A nice nearby point-like \( G \), calibrator (3), observed alternately, but too weak for good \( B \) calibration (flux density unknown)
  - One observation of strong flux density calibrator (5)
  - One observation of a strong source for \( B \) calibration (4)
- Schedule (each digit is a fixed duration):

3-222-2-3222-3-2222-3-222-3-3222-3-34444-3-222-3-2222-3-2222-655

Spectral-Line Calibration Example (cont)

- Target source = 2
  - \( G \) calibrator = 3
  - \( B \) calibrator = 4
  - Flux calibrator = 5
- Calibration sequence:
  - On 4, solve for \( G \):
    \[
    [G_{\nu}^{\text{obs}}] = G_{\nu}^{\text{ab恍}} [G_{\nu}^{\text{ab恍}}]
    \]
  - On 4, solve for \( B \), using \( G \):
    \[
    [T_{\nu}^{\text{obs}}] = B_{\nu}^{\text{obs}} [G_{\nu}^{\text{obs}}] [T_{\nu}^{\text{obs}}]
    \]
  - On 3, solve for \( G \), using \( B \):
    \[
    [G_{\nu}^{\text{obs}}] = G_{\nu}^{\text{ab恍}} [G_{\nu}^{\text{ab恍}}] [G_{\nu}^{\text{obs}}]
    \]
  - Scale 3’s \( G \)s according to 5’s \( G \)s:
    \[
    [G_{\nu}^{\text{obs}}] = G_{\nu}^{\text{cal}} [G_{\nu}^{\text{obs}}] [G_{\nu}^{\text{obs}}]
    \]
  - Transfer \( B \), to 2:
    \[
    [T_{\nu}^{\text{obs}}] = [G_{\nu}^{\text{obs}}] [G_{\nu}^{\text{ab恍}}] [T_{\nu}^{\text{obs}}]
    \]
Any evidence of unsampled variation? Is interpolation of solutions appropriate?
Self-calibration may be required, if possible.

Are solutions continuous?
Noise-like solutions are just that—noise
Discontinuities indicate instrumental glitches
Any additional editing required?
Are calibrator data fully described by antenna-based effects?
Phase and amplitude closure errors are the baseline-based residuals
Are calibrators sufficiently point-like? If not, self-calibrate: model calibrator visibilities (by imaging, deconvolving, and transforming) and re-serve for calibration; iterate to isolate source structure from calibration components
Tim Cornwell’s lecture: “Self-Calibration” (Wednesday)

Evaluating Calibration Performance

Ionospheric Faraday Rotation, $F$

The ionosphere is dihreptifl, one hand of circular polarization is delayed w.r.t. the other, introducing a phase shift:
$$\Delta \phi = 0.15 \int \frac{d\lambda}{B_D \lambda}, \text{deg}$$
Where the linear polarization-position angle
More important at longer wavelengths ($\lambda$)
$$\Phi C = 10^3 \text{cm}^2; B_D \sim 10^4 \text{G}, \lambda \approx 20 \text{cm} \rightarrow \Delta \phi \approx 60 \text{deg}$$
More important at solar maximum and at sunrise/sunset, when ionosphere is most active and variable
Beware of direction-dependence within field-of-view
Crystal Brogan’s lecture: “Low Frequency Interferometry” (Friday)

$$E = \begin{pmatrix} e^{j\alpha} & 0 \\ 0 & e^{-j\alpha} \end{pmatrix}, \tilde{F} = \begin{pmatrix} \cos \Delta \phi \sin \Delta \phi \\ \sin \Delta \phi \cos \Delta \phi \end{pmatrix}$$

Tropospheric Effects, $T$

The troposphere causes polarization-independent amplitude and phase effects due to emission/opacity and refraction, respectively
Typically 2-3m excess path length at zenith compared to vacuum
Higher noise contribution; less signal transmission. Lower SNR
Most important at $> 15$ GHz where water vapor absorbs/emits
More important nearer horizon where tropospheric path length greater
Clouds, weather = variability in phase and opacity; may vary across array
Water vapor radiometry? Phase transfer from low to high frequencies?
Debra Shepherd’s lecture: “Millimeter Interferometry” (Friday)

$$\tilde{T} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

A Dictionary of Calibration Components

$J$ contains many components:
$\mathbf{F} = \text{Ionospheric Faraday rotation}$
$\mathbf{T} = \text{Tropospheric effects}$
$\mathbf{P} = \text{parabolic angle}$
$\mathbf{E} = \text{antenna voltage pattern}$
$\mathbf{D} = \text{polarization leakage}$
$\mathbf{G} = \text{electronic gain}$
$\mathbf{B} = \text{bandpass response}$
$\mathbf{A} = \text{geometric compensation}$

Order of terms follows signal path (right to left)
Each term has matrix form of $J$ with terms embodying its particular algebra (on vs. off-diagonal terms, etc.)
Direction-dependent terms involve FT in solution
The full matrix equation (especially after correlation) is daunting, but usually only need to consider the terms individually or in pairs, and rarely in open form (matrix formulation = shorthand)
Parallactic Angle, \( P \)

- Orientation of sky in telescope's field of view
  - Constant for equatorial telescopes
  - Varies for all as-mounted telescopes:
    \[
    \chi(t) = \arctan \left( \frac{\sin(l) \cos(b) - \sin(b) \cos(l) \cos(h(t))}{\cos(b) \cos(h(t))} \right)
    \]
    \( l \) = latitude, \( b \) = hour angle, \( \delta \) = declination
- Rotates the position angle of linearly polarized radiation (c.f. \( \psi \))
- Analytically known, and its variation provides leverage for determining polarization-dependent effects
  \[
  \rho_{\psi \chi} = \begin{pmatrix} e^{i\psi} & 0 \\ 0 & e^{i\chi} \end{pmatrix}
  \]
  \[
  \rho_{\psi \chi} = \begin{pmatrix} \cos \chi & -\sin \chi \\ \sin \chi & \cos \chi \end{pmatrix}
  \]

Antenna Voltage Pattern, \( E \)

- Antennas of all designs have direction-dependent gain
  - Important when region of interest on sky comparable to or larger than \( \lambda / D \)
  - Important at lower frequencies where radio source surface density is greater and wide-field imaging techniques required
  - Beam squint: \( E \) and \( I \) plot parallel, yielding spurious polarization
  - For convenience, direction dependence of polarization leakage (\( G \)) may be included in \( E \)
  - Orthogonality required in \( E \) (off-diagonal terms then zero)
  - Rick Perley's lecture: "Wide Field Imaging" (Friday)
  - Tim Cornwell's lecture: "Wide Field Imaging II" (Friday)
  \[
  E \rightarrow \begin{pmatrix} e^{i\psi(l,m)} & 0 \\ 0 & e^{i\chi(l,m)} \end{pmatrix}
  \]

Polarization Leakage, \( D \)

- Polarizer is not ideal, so orthogonal polarizations not perfectly isolated
  - Well-designed feeds have \( d \approx \frac{\lambda}{D} \), \( d \approx \frac{\lambda}{D} \), \( d \approx \frac{\lambda}{D} \)
  - A geometric property of the feed design, so frequency dependent
  - For NLS systems, total intensity imaging affected as \( = \frac{d}{d} \), so almost always important
  - Steve Myers' lecture: "Polarization in Interferometry" (today)
  \[
  \hat{D} = \begin{pmatrix} 1 & d^* \\ d & 1 \end{pmatrix}
  \]

"Electronic" Gain, \( G \)

- Catch-all for most amplitude and phase effects introduced by antenna electronics (amplifiers, mixers, quantizers, digitizers)
  - Most commonly treated calibration component
  - Dominates other effects for standard VLA observations
  - Includes scaling from engineering (correlation coefficient) to radio astronomy units (\( \lambda / D \)), by scaling solution amplitudes according to observations of a flux density calibrator
  - Often also includes ionospheric and tropospheric effects which are typically difficult to separate between themselves
  - Excludes frequency dependent effects (see \( B \))
  \[
  G \rightarrow \begin{pmatrix} e^{i\psi} & 0 \\ 0 & e^{i\chi} \end{pmatrix}
  \]

Bandpass Response, \( B \)

- \( B \) like component describing frequency dependence of antenna electronics, etc.
  - Filters used to select frequency passband not square
  - Optical and electronic reflections introduce ripples across band
  - Often assumed time-independent, but not necessarily so
  - Typically (but not necessarily) normalized
  \[
  B \rightarrow \begin{pmatrix} b'(y) & 0 \\ 0 & b'(y) \end{pmatrix}
  \]

Geometric Compensation, \( K \)

- Must get geometry right for Synthesis Fourier Transform relation to work in real time; residual errors here require "Fringe-fitting"
  - Antenna positions (geodesy)
  - Source directions (time-dependent in topocenter') (astrometry)
  - Clocks
  - Electronic pathlengths
  - Importance scales with frequency and baseline length
  - Craig Walker's lecture: "Very Long Baseline Interferometry" (Thursday)
  \[
  K \rightarrow \begin{pmatrix} k & 0 \\ 0 & k \end{pmatrix}
  \]
Non-closing Effects: $M, A$

- Correlator-based errors which do not decompose into antenna-based components:
  - Most digital correlators designed to limit such effects to well-understood and uniform scaling laws (assumed in $M$)
  - Simple noise
  - Additional errors can result from averaging in time and frequency over variation in antenna-based effects and visibilities (practical instruments are finite)
  - Correlated "noise" (e.g., RFI)
  - Virtually indistinguishable from source structure effects
  - Geometric observers consider determination of radio source structure—a baseline-based effect—as a required calibration if antenna positions are to be determined accurately
  - Diagonal 4x4 matrices. $M$ multiplies. $A$ adds

Calibrator Rules of Thumb

- $T, G, K$:
  - Strong and point-like sources, as near to target source as possible
  - Observe often enough to track phase and amplitude variations: calibration intervals at up to 10% of minutes at low frequencies (beware of Corr. "noise")
  - Observe at least one calibrator of known flux density at least once
- $B$:
  - Strong enough for good sensitivity in each channel (often, $T, G$ calibrator is ok, point-like if visibility might change across band
  - Observe often enough to track variations (e.g., waveguide reflections change with temperature and are thus a function of time-of-day)
- $D$:
  - Best calibrator for full calibration is strong and polarized
  - If polarized, observe over a broad range of parallactic angle to disentangle $O$s and source polarization (often, $T, G$ calibrator is ok)
- $F$:
  - Choose strongly polarized source and observe often enough to track variation

The Whole M.E.

- The net $J$ can be written:
  \[ \mathbf{J} = \mathbf{M} \left[ \mathbf{K} \mathbf{B} \mathbf{G} \mathbf{D} \mathbf{E} \mathbf{P} \mathbf{F} \mathbf{G} \mathbf{D} \mathbf{E} \right] \]
  \[ = \mathbf{M} \left[ \mathbf{K} \mathbf{B} \mathbf{D} \mathbf{E} \mathbf{P} \mathbf{F} \mathbf{G} \mathbf{D} \mathbf{E} \right] \]
  \[ = \mathbf{M} \mathbf{K} \mathbf{B} \mathbf{D} \mathbf{E} \mathbf{P} \mathbf{F} \mathbf{G} \mathbf{D} \mathbf{E} \]
- The total Measurement Equation has the form:
  \[ \mathbf{V} = \mathbf{M} \mathbf{K} \mathbf{B} \mathbf{D} \mathbf{E} \mathbf{P} \mathbf{F} \mathbf{G} \mathbf{D} \mathbf{E} \]

Data Examination and Editing

- After observation, initial data examination and editing very important
  - Will observations meet goals for calibration and science requirements?
  - Some real-time flagging occurred during observation (antennas off-source, LO out-of-lock, etc.). Any such bad data left over? (check operator’s logs)
  - Any persistent ‘dead’ antennas (J<0 during otherwise normal observing)? (check operator’s logs)
  - Amplitude and phase should be continuously varying/edit outliers
  - Any antennas shadowing others? Edit such data
  - Be conservative: those antennas/temperatures which are bad on calibrators are probably bad on weak target sources/edit them
  - Periods of poor weather? (check operator’s log)
  - Distinguish between bad (hopeless) data and poorly-calibrated data. E.g., some antennas may have significantly different amplitude response which may not be fatal—it may only need to be calibrated
  - Radio Frequency Interference (RFI)?
  - Choose reference antenna wisely (ever-present, stable response)

Radio Frequency Interference

- RFI originates from man-made signals generated in the antenna electronics or by external sources (e.g., satellites, cell-phones, radio and TV stations, automobile ignitions, microwave ovens, etc.)
  - Adds to total noise power in all observations, thus decreasing sensitivity to desired natural signal, possibly pushing electronics into non-linear regimes
  - As a contribution to the $n$ term, can correlate between antennae if of common origin and baseline short enough (insufficient decorrelation via $K$)
  \[ \{K_{ij} K_{ij}’\} = \{K_{ii} + n_{ii}\} = \{K_{ii}’ + n_{ii}\} \]
  \[ = \{K_{ij} K_{ij}’\} + \{K_{ii}’ n_{ij}\} + \{K_{ii} n_{ij}’\} \]
  \[ = \{K_{ij} K_{ij}’\} + \{K_{ii}’ n_{ij}\} \]
  - When RFI is correlated, it obscures natural emission in spectral line observations

A Data Editing Example

- RFI originates from man-made signals generated in the antenna electronics or by external sources (e.g., satellites, cell-phones, radio and TV stations, automobile ignitions, microwave ovens, etc.)
  - Adds to total noise power in all observations, thus decreasing sensitivity to desired natural signal, possibly pushing electronics into non-linear regimes
  - As a contribution to the $n$ term, can correlate between antennae if of common origin and baseline short enough (insufficient decorrelation via $K$)
  \[ \{K_{ij} K_{ij}’\} = \{K_{ii} + n_{ii}\} = \{K_{ii}’ + n_{ii}\} \]
  \[ = \{K_{ij} K_{ij}’\} + \{K_{ii}’ n_{ij}\} + \{K_{ii} n_{ij}’\} \]
  \[ = \{K_{ij} K_{ij}’\} + \{K_{ii}’ n_{ij}\} \]
Radio Frequency Interference

- Has always been a problem (Reber, 1944, in total power!)

Radio Frequency Interference (cont)

- Growth of telecom industry threatening radioastronomy!

- RFI Mitigation
  - Careful electronics design in antennas, including notch filters
  - High-dynamic range digital sampling
  - Observatories world-wide lobbying for spectrum management
  - Choose interference-free frequencies: try to find 50 MHz (1 GHz) of clean spectrum in the VLA (EVLA): 1.6 GHz band!
  - Observe continuum experiments in spectral-line modes so affected channels can be edited

- Various off-line mitigation techniques under study
  - E.g., correlated RFI power appears at celestial pole in image domain...

Summary

- Determining calibration is as important as determining source structure—can’t have one without the other
- Calibration dominated by antenna-based effects, permits separation of calibration from astronomical information
- Calibration formalism algebra-rich, but can be described piecemeal in comprehensible segments, according to well-defined effects
- Calibration determination is a single standard fitting problem
- Calibration an iterative process, improving various components in turn
- Point sources are the best calibrators
- Observe calibrators according requirements of components
- Data examination and editing an important part of calibration